Quantum Computing Trends

Yuri Alexeev
Argonne National Laboratory

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Yuri Alexeev

- Principal project specialist at the Argonne National Laboratory
- Senior scientist at University of Chicago
- Principal investigator at the National Quantum Center Q-NEXT
- Member of Chicago Quantum Exchange

Research interests:

- Quantum simulators
- High performance computing
- Quantum chemistry algorithms
- Quantum combinatorial optimization algorithms
- Quantum machine learning

MAKING QUANTUM TECHNOLOGY A REALITY

CHICAGO
QUANTUM
EXCHANGE

- Founded in 2017
- Spanning disciplines and institutions
- Fosters collaboration and joint projects
- Bridging academia, national laboratories, and industry
- Education and training quantum scientists and engineers

THE UNIVERSITY OF CHICAGO

ILLINOIS

Argonne NATIONAL LABORATORY

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Fermilab

Northwestern University

CHICAGO QUANTUM EXCHANGE | THE UNIVERSITY OF CHICAGO Argonne NATIONAL LABORATORY Fermilab ILLINOIS WISCONSIN UNIVERSITY OF WISCONSIN–MADISON Northwestern University

CHICAGO QUANTUM EXCHANGE

Harnessing physics at the subatomic scale to create new technologies, industries, and career pipelines

CQE BY THE NUMBERS

$260M+
FEDERAL FUNDING TO CQE INSTITUTIONS IN 2020

130+
RESEARCHERS

6
MEMBERS ACROSS CHICAGOLAND+

20
CORPORATE PARTNERS

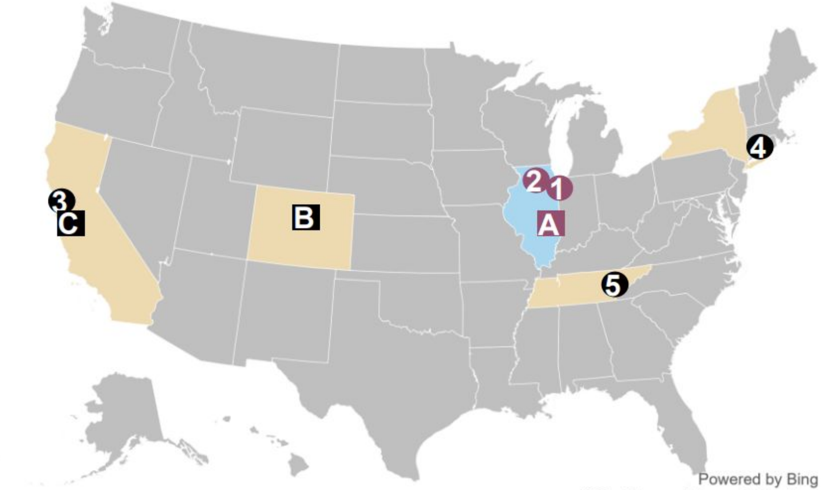


Image courtesy of P33

Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

CHICAGO QUANTUM EXCHANGE | THE UNIVERSITY OF CHICAGO | Argonne NATIONAL LABORATORY | Fermilab | ILLINOIS | WISCONSIN UNIVERSITY OF WISCONSIN–MADISON | Northwestern University

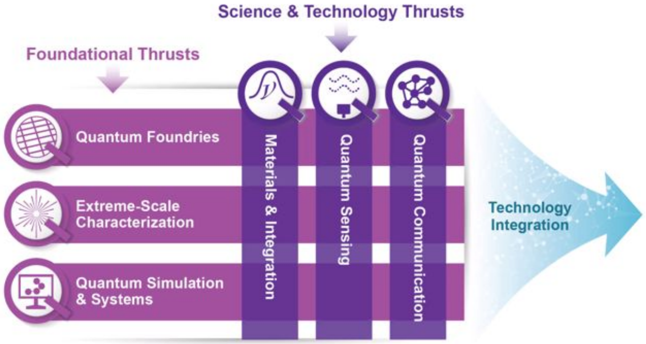
Q-NEXT: Quantum Information Science Research Center at Argonne

- **Major Cross-Cutting Challenge:** Manipulating and interconnecting entangled states of matter.
- **Mission:** Deliver quantum interconnects and establish a national resource to provide pristine materials for new quantum devices.
- Nearly 100 researchers from 3 national laboratories, 10 universities, and 10 industry partners
- $115M from DOE and an additional $93M from industry partners

Thrusts and Argonne Leadership:

Executive Team:

Thrust Leaders:



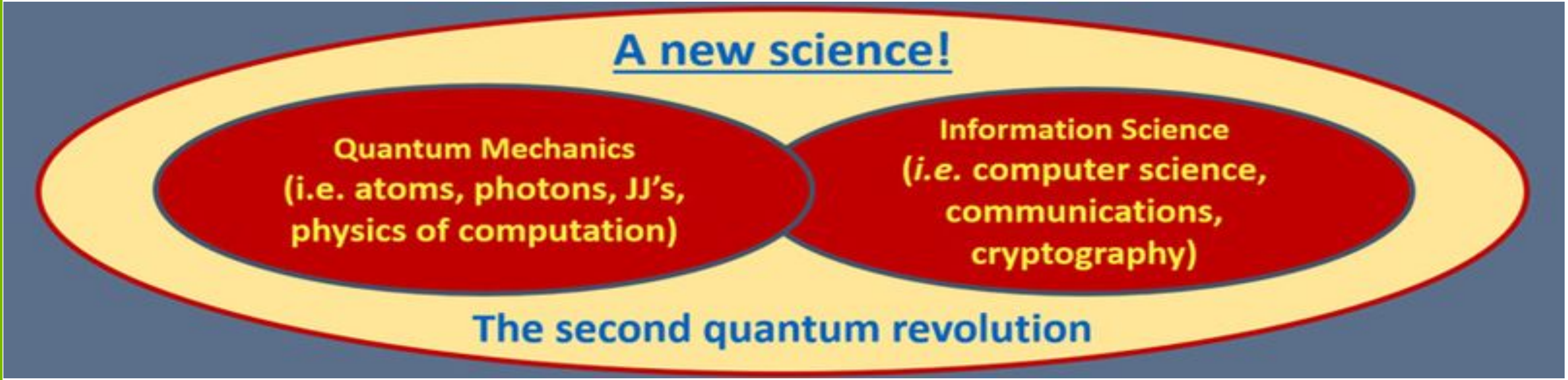
Partner institutions:

Q-NEXT Mission

- ✓ Deliver quantum interconnects
- ✓ Establish national foundries
- ✓ Demonstrate communication links, networks of sensors, and simulation testbeds

Quantum Information Science (QIS)

- Quantum mechanics explains how world works at microscopic level, which governs behavior of all physical systems, regardless of their size
- Information science revolutionized how information is collected, stored, analyzed, manipulated, protected, and moved
- We see convergence of two 20th century greatest revolutions in the form of Quantum Information Science (QIS)



Quantum Information Science

QIS exploits unique quantum effects such as superposition, interference, and entanglement to obtain, compute, and transmit information in the ways that are superior compared to classical technology (digital, Newtonian)

The key concept is entanglement (“spooky action at a distance”, EPR pair). Works only for only very small object (electrons, photons, atoms etc). It is proven to be essential to achieve “quantum advantage” or for “quantum teleportation”

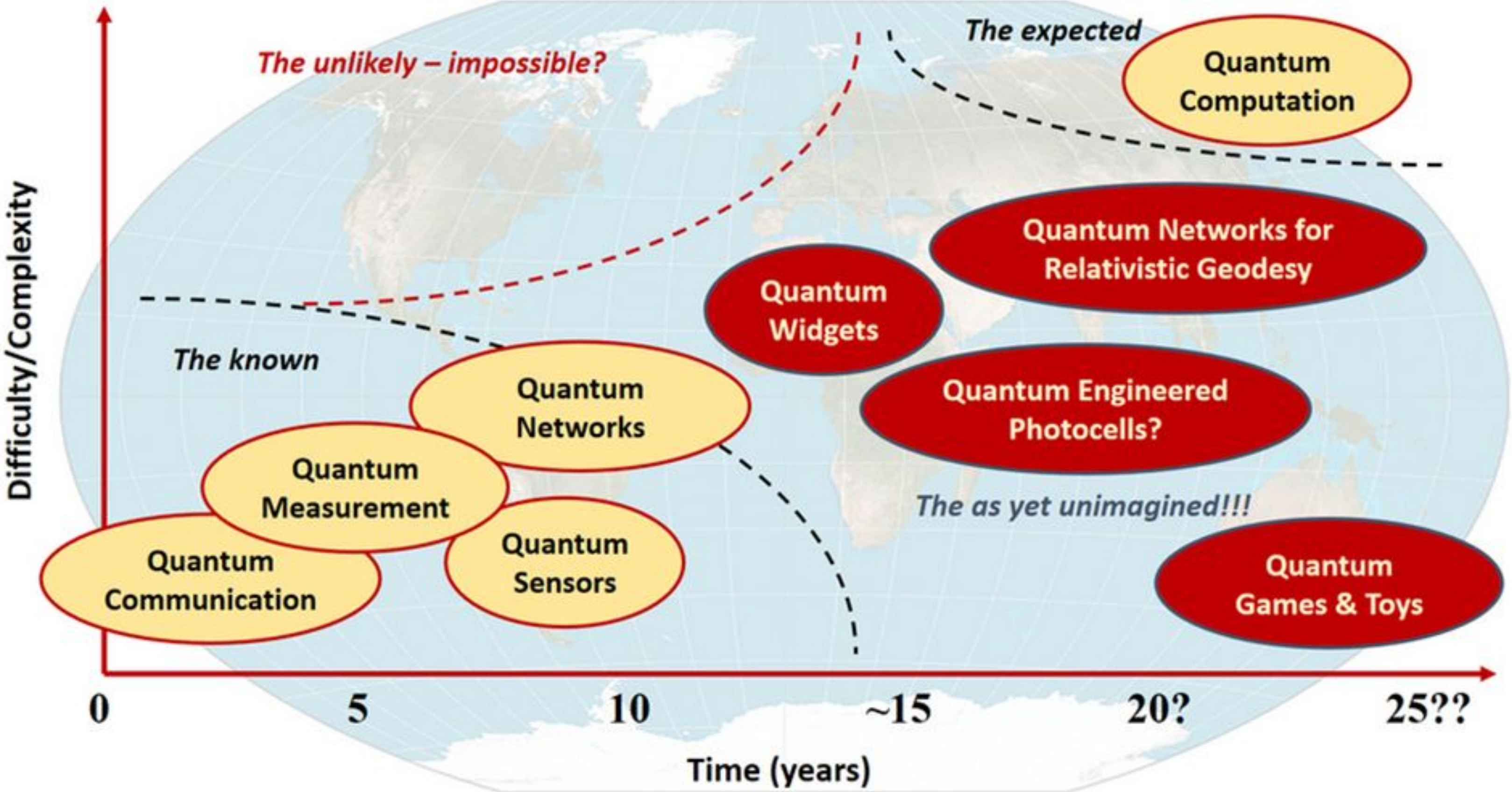
Classical	
Outcome	Probability
00	1/4
01	1/4
10	1/4
11	1/4

Quantum	
Outcome	Probability
00	1/2
01	0
10	0
11	1/2

Key concepts

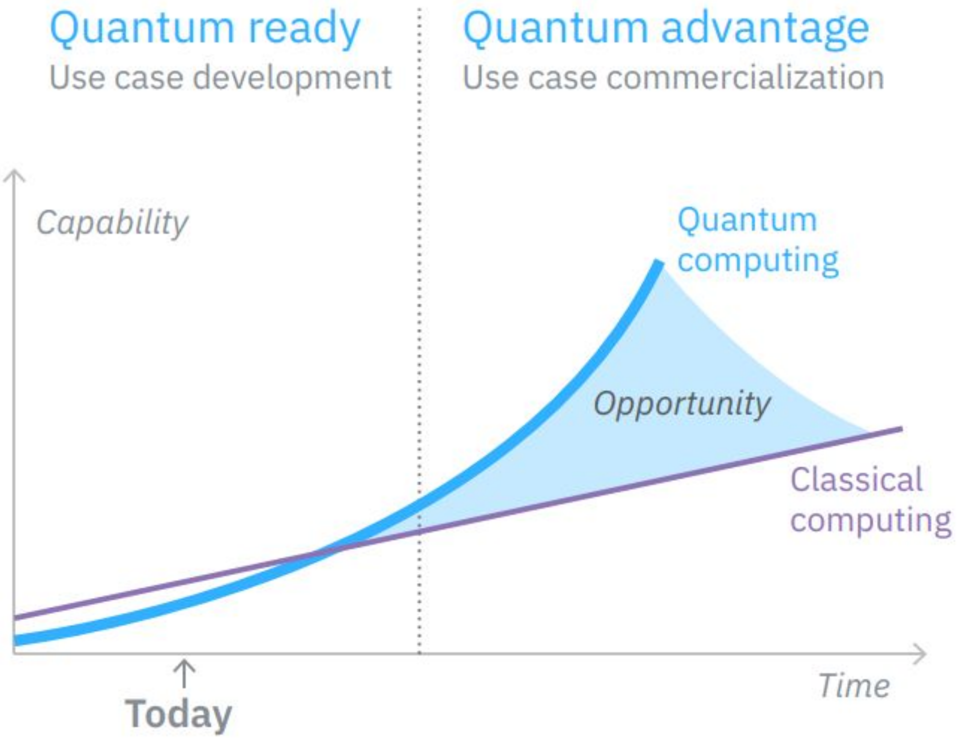
- Qubit - basic unit of quantum information, which is the quantum version of the classical binary bit. It can exist in superposition – any state between 0 and 1
- Qubit fidelity – how long qubit stays coherent/operational
- Quantum effects - superposition, interference, and entanglement
- NISQ - Noisy Intermediate-Scale Quantum technology, often refers in the context of modern very noisy quantum computers
- QASM - Quantum Assembly used for programming quantum computers
- Quantum supremacy - demonstration of that a programmable quantum device can solve a problem (any problem) that no classical computer can solve in any feasible amount of time
- Quantum advantage - same as supremacy, but for useful applications

Quantum applications



Why quantum computing?

Commercialization of a quantum use case

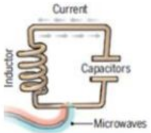
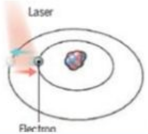


Why quantum computing?

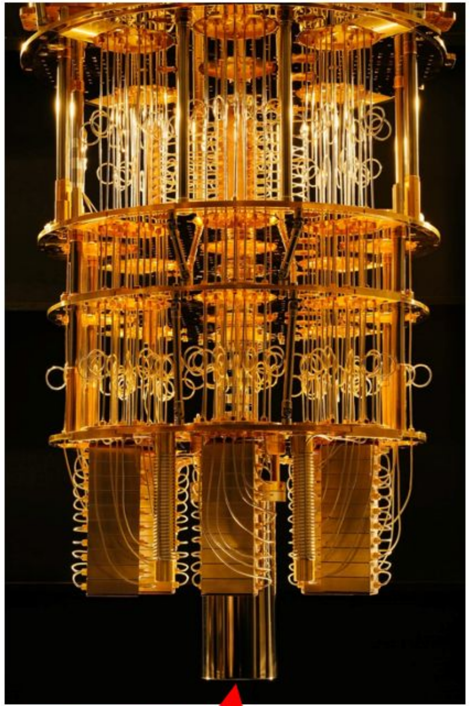
Quantum computing's potential for significant speedup over classical computers

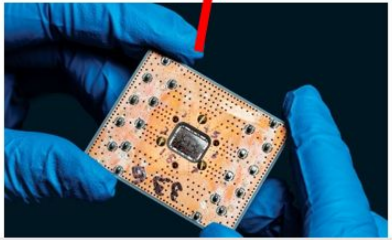
Type of scaling	Time to solve problem				
Classical algorithm with exponential runtime	10 secs	2 mins	330 years	3300 years	Age of the universe
Quantum algorithm with polynomial runtime	1 min	2 mins	10 mins	11 mins	~24 mins

Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space 	 Computers are ranked by number of qubits decoherency time	**Superconducting (IBM, Google, Rigetti)**	**Trapped ions (IonQ, U. of Innsbruck)**
Qubit Modality	Materials	Al on the Silicon substrate	Yb+, Ca+, Sr+, Be+, Ba+, Mg+
	Type	Transmon	Optical transitions
	Control	Microwaves	Microwaves + optics
	State	Junction phase	Atomic state of election
Approximate Decoherency Times (ns)		~100-200	Very long
	1qb gate	10	5,000
	2qb gate	40	50,000
Fidelity	1qb gate	99.9%	99.999%
	2qb gate	99.0%	99.5%
Speed (MHz)	1qb gate	100.00	0.20
	2qb gate	25.00	0.02

IBM quantum computers





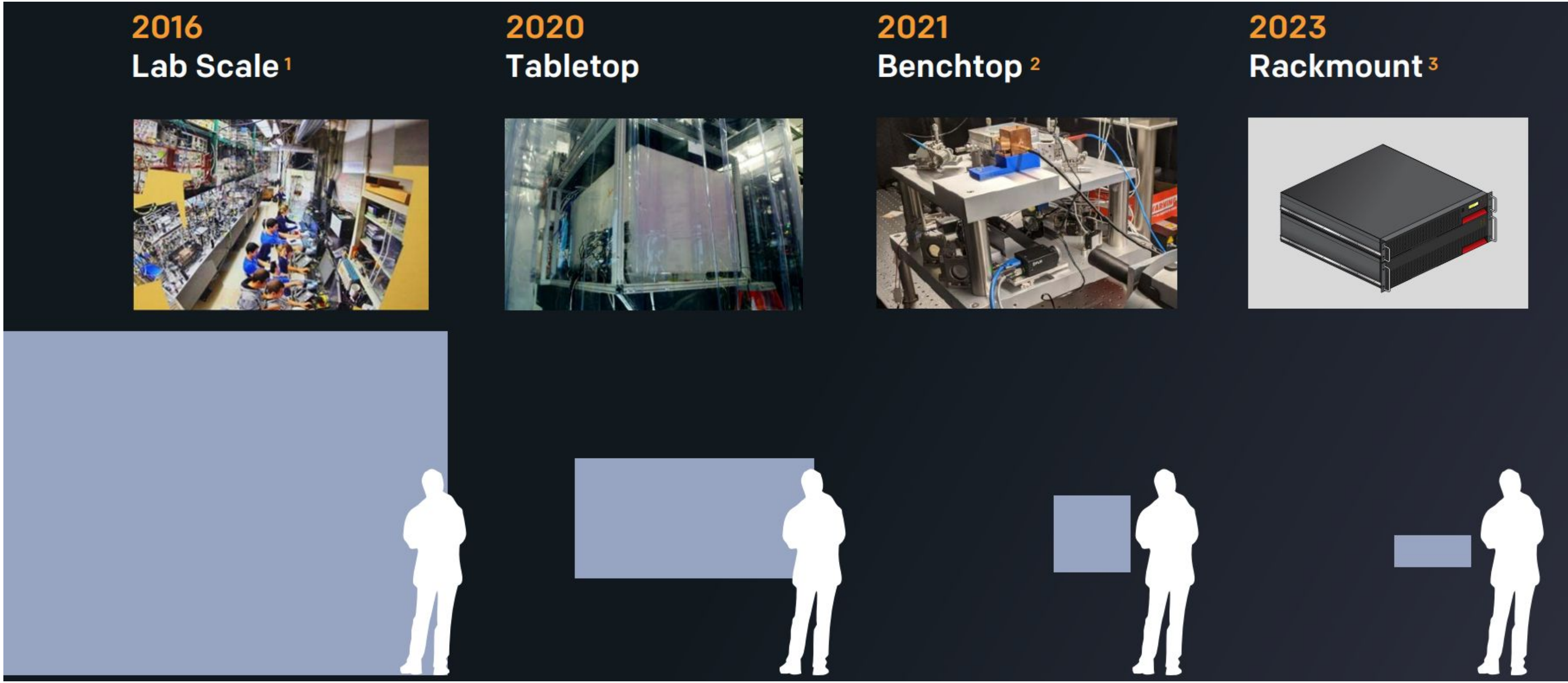
The key piece of the Quantum Computer is the Dilution Refrigerator

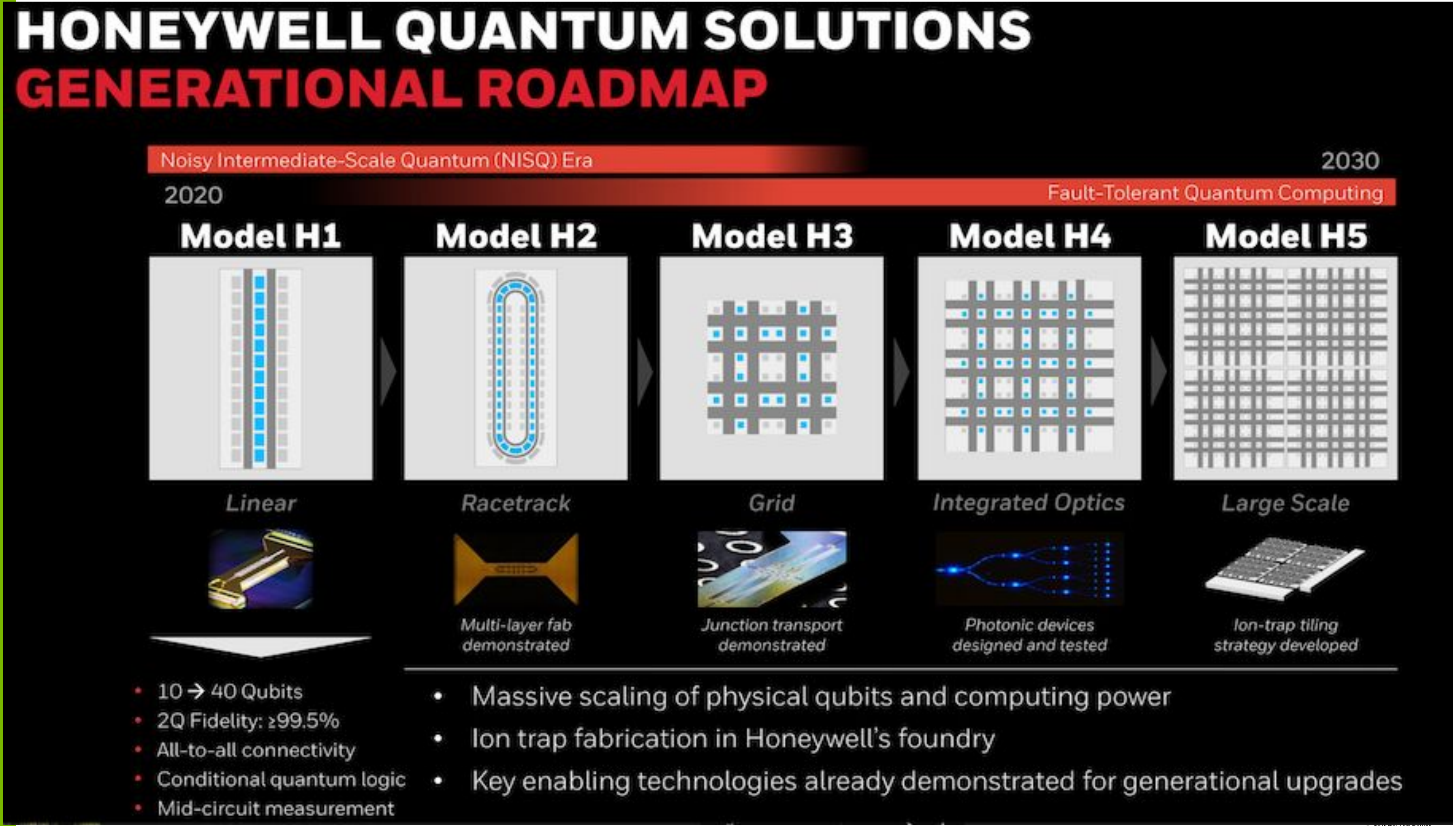
Working Temperature 15 mK uses mix of

^{3}He/^{4}He

Source: IBM Research

IonQ Quantum Computers

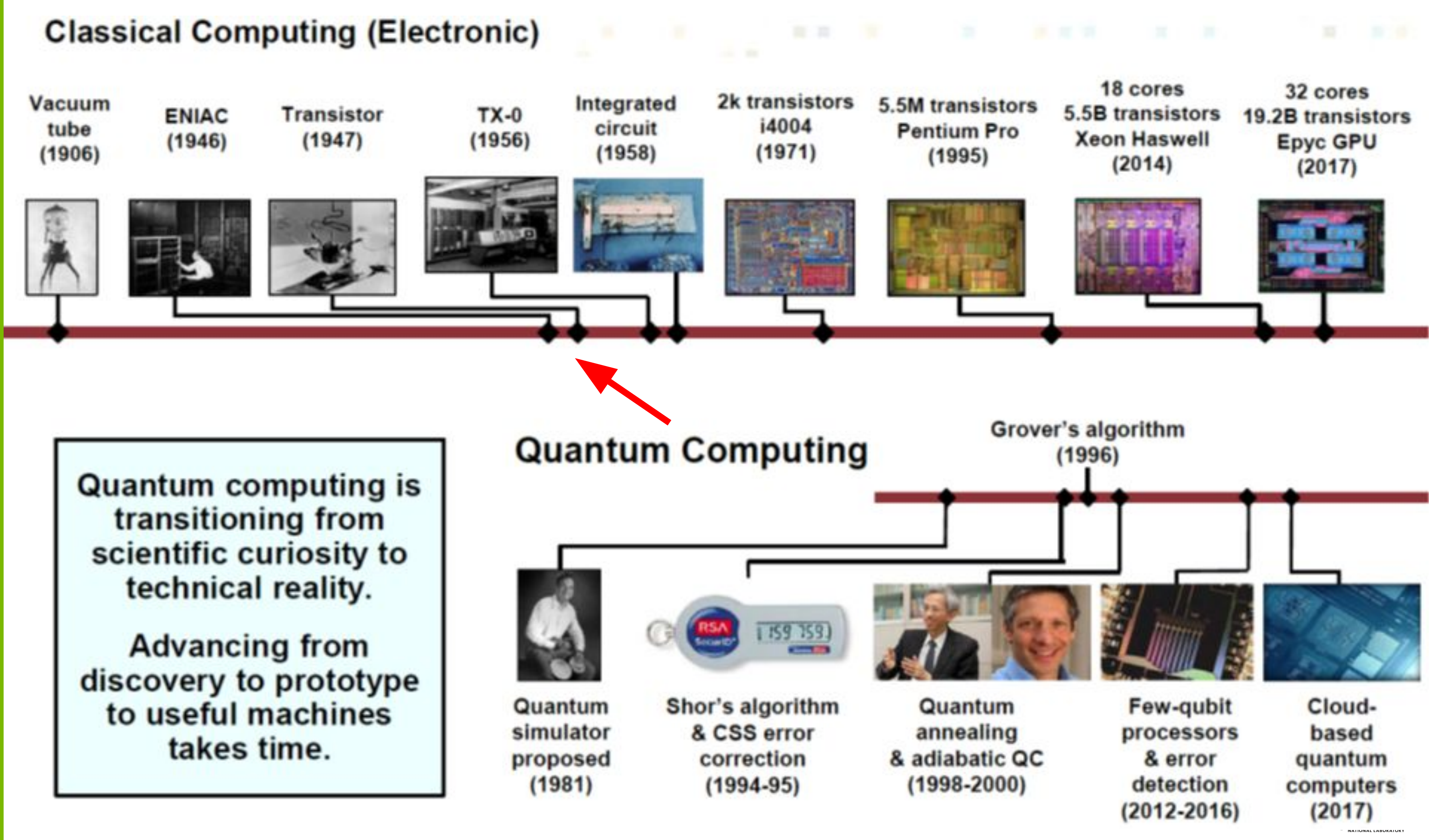



HONEYWELL QUANTUM SOLUTIONS
GENERATIONAL ROADMAP
Noisy Intermediate-Scale Quantum (NISQ) Era
2030
2020
Fault-Tolerant Quantum Computing
Model H1
Model H2
Model H3
Model H4
Model H5
Linear
Racetrack
Grid
Integrated Optics
Large Scale
Multi-layer fab demonstrated
Junction transport demonstrated
Photonic devices designed and tested
Ion-trap tiling strategy developed
10 → 40 Qubits
2Q Fidelity: ≥99.5%
All-to-all connectivity
Conditional quantum logic
Mid-circuit measurement
Massive scaling of physical qubits and computing power
Ion trap fabrication in Honeywell's foundry
Key enabling technologies already demonstrated for generational upgrades

Available and announced quantum computers

Company*	Operational	Cloud Access	Framework	Announced
IBM	72 qubits	Open to Q hub members	Qiskit	120+ qubit in 2021
Rigetti	31 (8) qubits	Access by request	AWS and Forest	50+ qubit near future
Google	72 qubits	No access	Cirq	120+ qubit in 2021
Alibaba	11 qubits	-	Alyun	-
IonQ	32 qubits	Paid Access	AWS and Azure	-
Honeywell	10 qubits (512 volume)	Paid Access	Azure	-
D-Wave	5000Q (annealer)	Open (1 minute per month)	AWS and Leap	10,000Q near future

**Intel not included – announced 49 qubit chip in January 2018*


Classical Computing (Electronic)
Vacuum tube (1906)
ENIAC (1946)
Transistor (1947)
TX-0 (1956)
Integrated circuit (1958)
2k transistors i4004 (1971)
5.5M transistors Pentium Pro (1995)
18 cores 5.5B transistors Xeon Haswell (2014)
32 cores 19.2B transistors Epyc GPU (2017)
Quantum Computing
Grover's algorithm (1996)
Quantum computing is transitioning from scientific curiosity to technical reality.
Advancing from discovery to prototype to useful machines takes time.
RSA SecurID
Quantum simulator proposed (1981)
Shor's algorithm & CSS error correction (1994-95)
Quantum annealing & adiabatic QC (1998-2000)
Few-qubit processors & error detection (2012-2016)
Cloud-based quantum computers (2017)

Development Roadmap

IBM Quantum

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026+

Enterprise Clients

2019–2022:
Use case exploration
Problem mapping
Skills building

2023–2026+:
Workflow integration
Application development
Skills building

Model developers

Quantum model services (2023–2026+):
Natural Sciences | Finance
Optimization | Machine Learning

Algorithm developers

Qiskit application modules (2020–2022):
Natural Sciences | Finance
Optimization | Machine Learning

Prebuilt quantum runtimes (2023–2024)

Prebuilt quantum + HPC runtimes (2025–2026+)

Kernel developers

Circuits (2019–2020)

Qiskit Runtime (2021)

Dynamic circuits (2022)

Circuit libraries (2023–2024)

Advanced control systems (2025–2026+)

Quantum systems

Falcon 27 qubits (2019)

Hummingbird 65 qubits (2020)

Eagle 127 qubits (2021)

Osprey 433 qubits (2022)

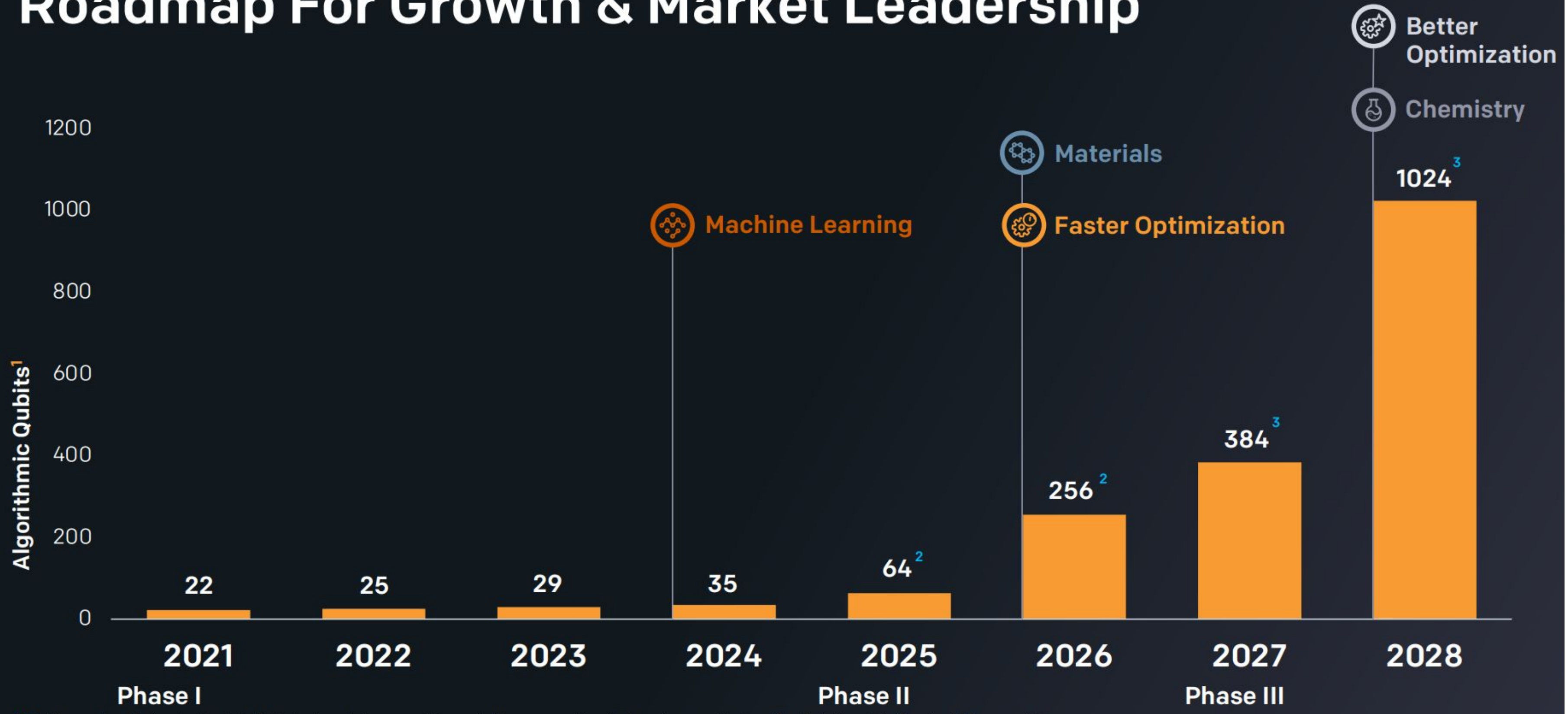
Condor 1121 qubits (2023)

Beyond 1K - 1M+ qubits (2024–2026+)

IBM Cloud

Circuits (2019–2020) | Programs (2021–2022) | Models (2023–2026+)

Roadmap For Growth & Market Leadership



Note Prepared on the basis of certain technical, market, competitive and other assumptions to be subsequently described in further detail, and which may not be satisfied. As a result, these projections are subject to a high degree of uncertainty and may not be achieved within the time-frames described or at all.

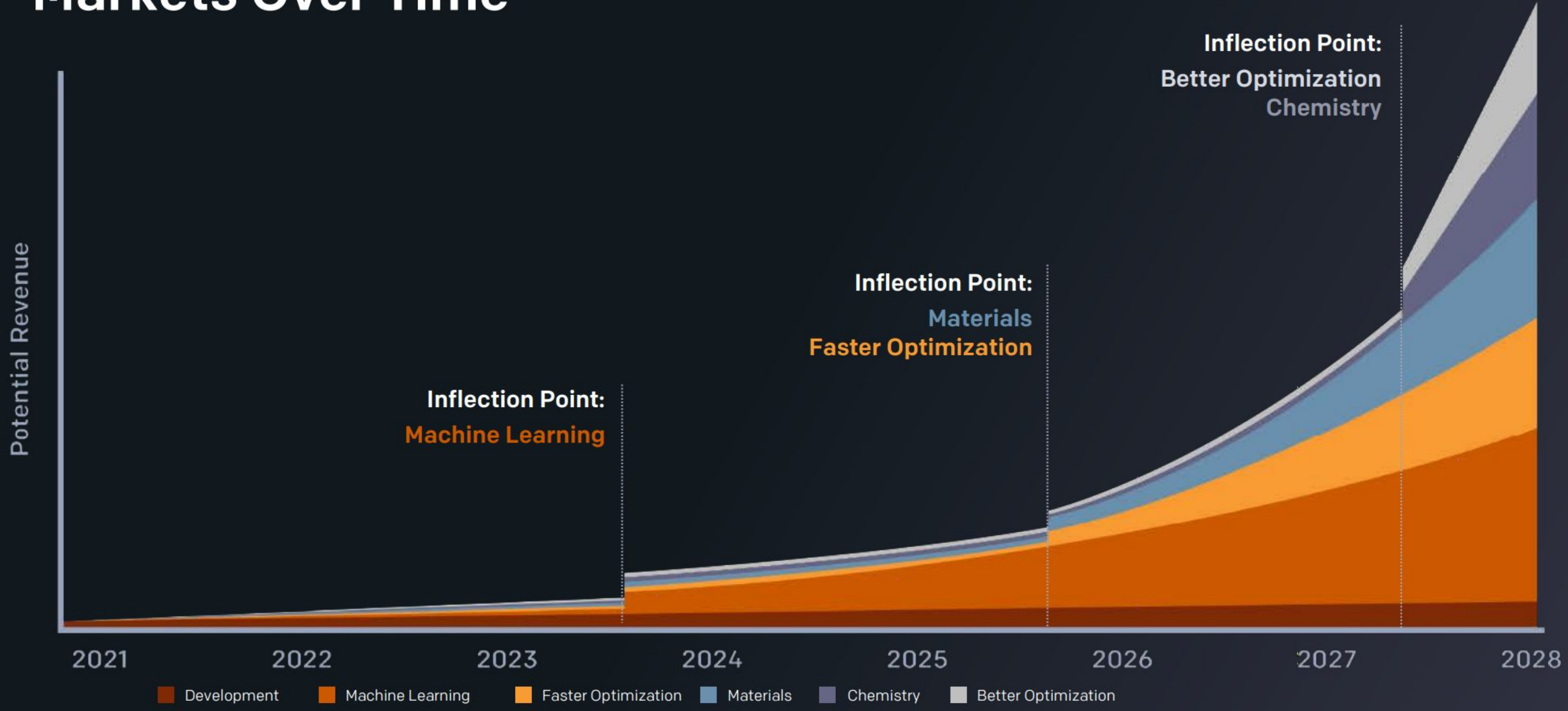
Note Market inflection points are estimated based on alignment of IonQ technical roadmap with publicly documented quantum research problems in each market

1 Algorithmic qubit number defined as the effective number of qubits for typical algorithms, limited by the 2Q fidelity

2 Employs 16:1 error-correction encoding

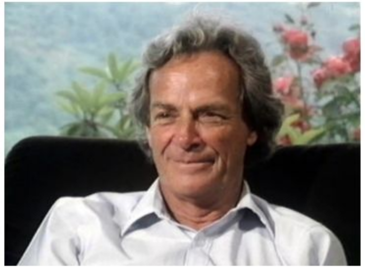
3 Employs 32:1 error-correction encoding

Technical Progress Unlocks Quantum Commercial Markets Over Time



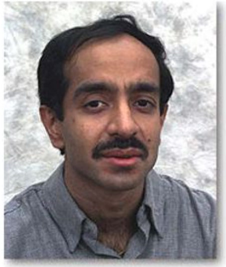
Note Inflection points estimated based on alignment of IonQ technical roadmap with publicly documented quantum research problems in each market. Market sizes not to scale.

“It’s been 20 years since Shor’s factoring algorithm. Where are all the amazing new quantum algorithms we were promised?”



Quantum simulation

Factoring



Grover search

Adiabatic alg / quantum walks

+ A few other things…

…Is that all? What else is there?

Who promised you more quantum algorithms? Not me!

Complexity of problems

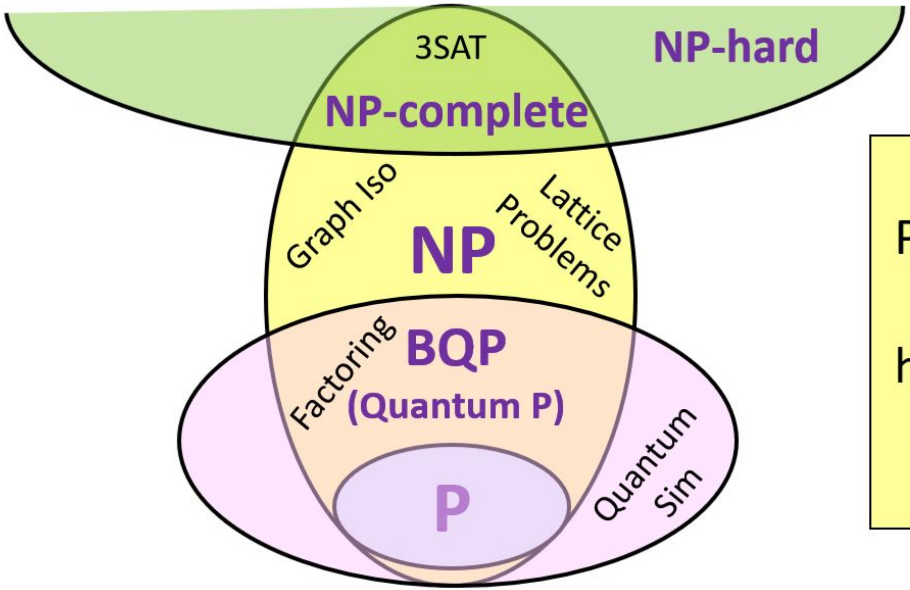
Table 1. Some computational complexity classes of importance in quantum computation

Class	*Informal definition*
P	Can be solved by a deterministic classical computer in polynomial time
BPP	Can be solved by a probabilistic classical computer in polynomial time
BQP	Can be solved by a quantum computer in polynomial time
NP	Solution can be checked by a deterministic classical computer in polynomial time
QMA	Solution can be checked by a quantum computer in polynomial time

Abbreviation: QMA, Quantum Merlin–Arthur.
'Polynomial time' is short for 'in time polynomial in the input size'.

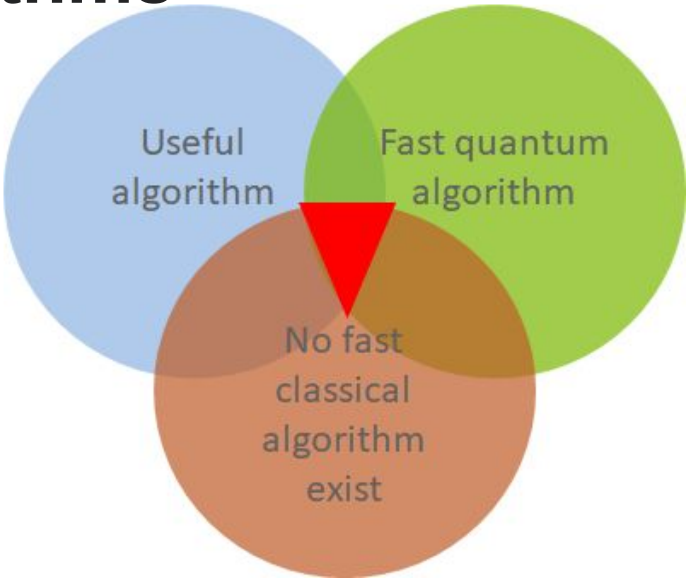
An Inconvenient Truth

If we set aside **NP**-complete problems, there just aren't that many compelling candidates left for exponential quantum speedups! **(And for many of those, we *do* have exponential speedups, and for many of the rest we have polynomial ones)**



P≠BQP, **NP⊄BQP**: Plausible conjectures, which we have no hope of proving given the current state of complexity theory

Quantum Algorithms



There are a few known classes algorithms hitting all three circles:

Four main fundamental algorithms expected to provide a speedup over their classical counterparts: Shor's factoring algorithm, Grover's search algorithm, HHL's linear system solver, and quantum simulation

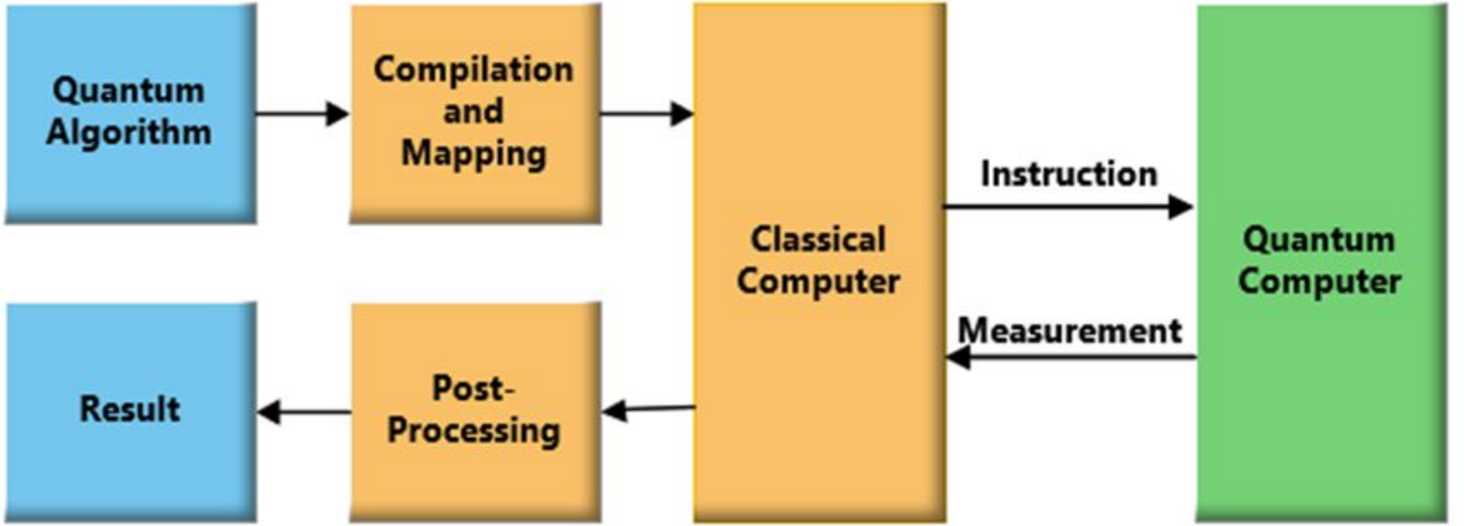
Early application areas for quantum computing

- Combinatorial optimization problems (no proven speedup):
  Finances, transportation, logistics

- Quantum machine learning (often requires QRAM)
  Finances, image recognition, traffic prediction

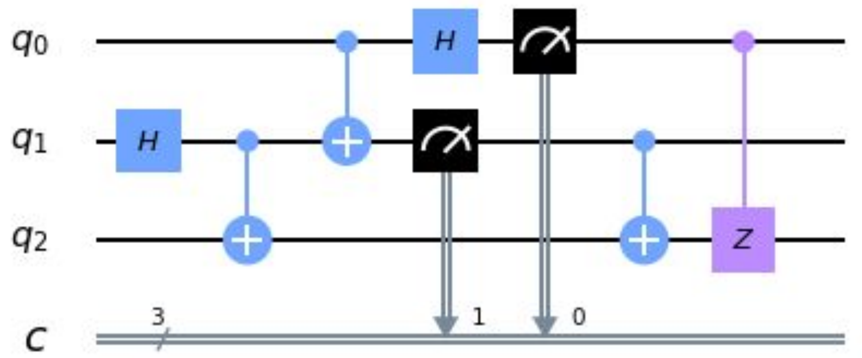
- Quantum simulations (proven speedup, but require fault tolerant large quantum devices)
  Quantum chemistry and physics problems, new materials design

Hybrid Quantum/Classical Computing System



A high-level block diagram of a quantum computing system, where colors represent different levels of abstractions. Typically three levels are involved: a user level (blue), classical computation and control (yellow), and QC system (green). A quantum algorithm is compiled and mapped into a native set of instruction for the target quantum computer. The measurement of quantum register after post-processing becomes the result.

What is a Quantum Circuit Simulator?

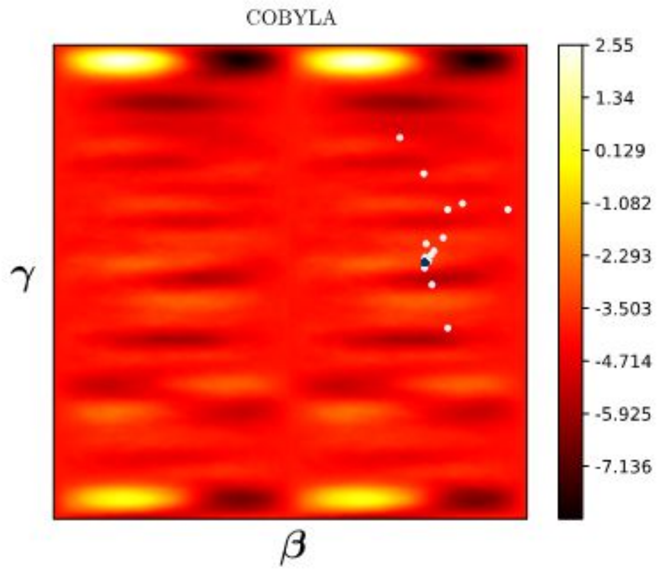


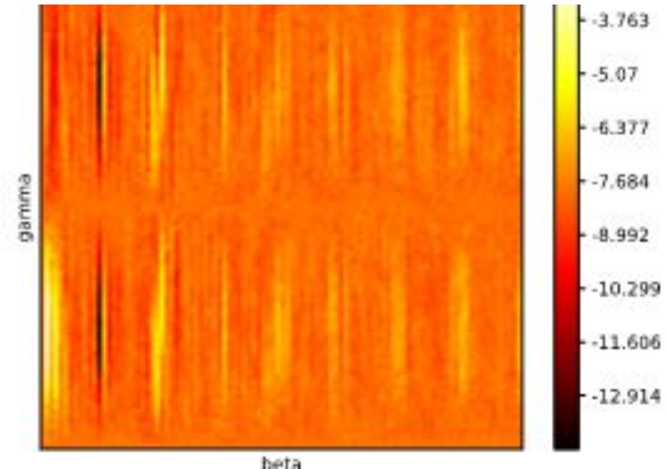
It is an universal quantum computer simulator which simulates the execution of quantum circuits with or without quantum noise

The input is a quantum circuit which is described using quantum assembly language (QASM)

Quantum Simulator Use Cases

- Verification of quantum advantage and supremacy claims
- Verification of large quantum devices
- Co-design quantum computers
- Energy efficiency studies of quantum computers
- Design of new quantum algorithms
- Finding parameters for variational quantum algorithms





Quantum Simulator Use Cases: Simulation of Supremacy Circuits

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

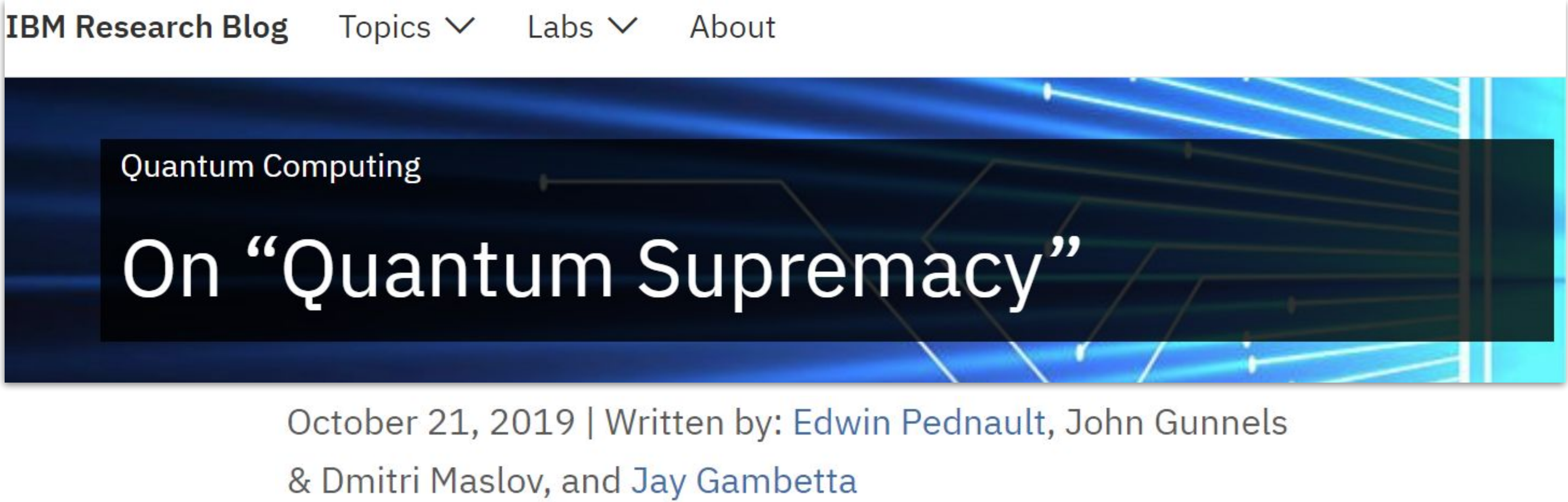
Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

799k Accesses | **693** Citations | **6025** Altmetric | Metrics

(CNN Business): Google claims it has designed a machine that needs only 200 seconds to solve a problem that would take the world's fastest supercomputer 10,000 years to figure out.

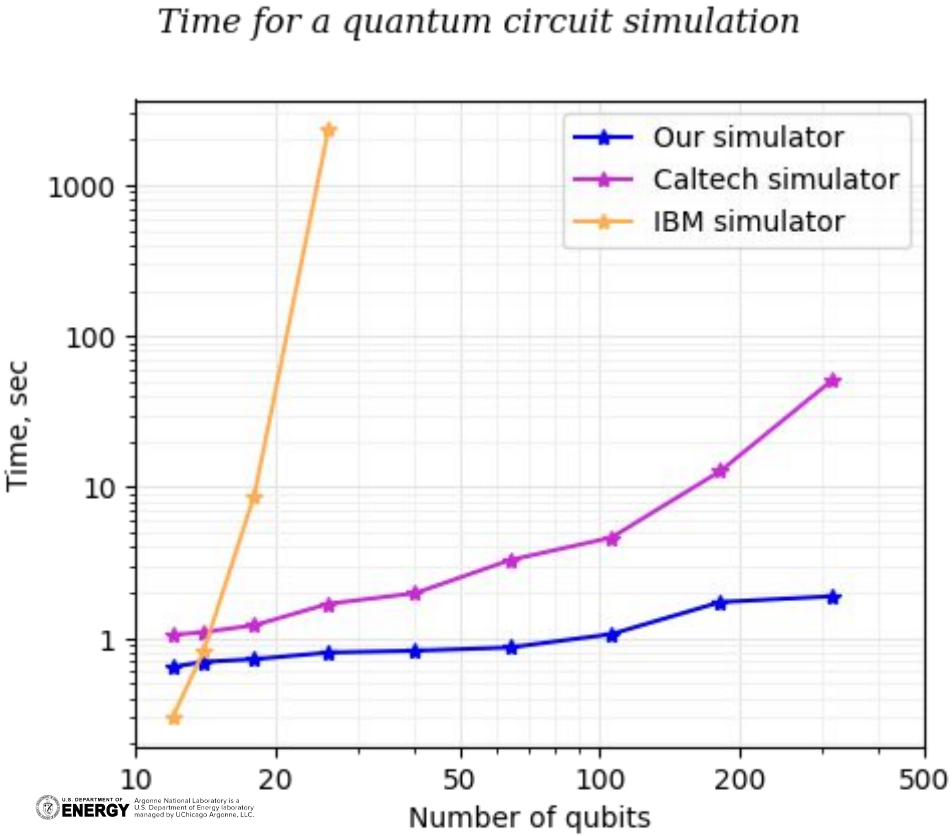
Quantum Simulator Use Cases: Simulation of Supremacy Circuits



“We argue that an ideal simulation of the same task can be performed on a classical system in 2.5 days and with far greater fidelity.”

Argonne developed simulator will be able to do these calculations in minutes on Summit

Quantum simulators developed at Argonne National Laboratory: QTensor and QuaC



Simulated 1,000,000 qubit QAOA circuit with depth p=6 in 1 hour and 20 minutes on 512 nodes of supercomputer Theta

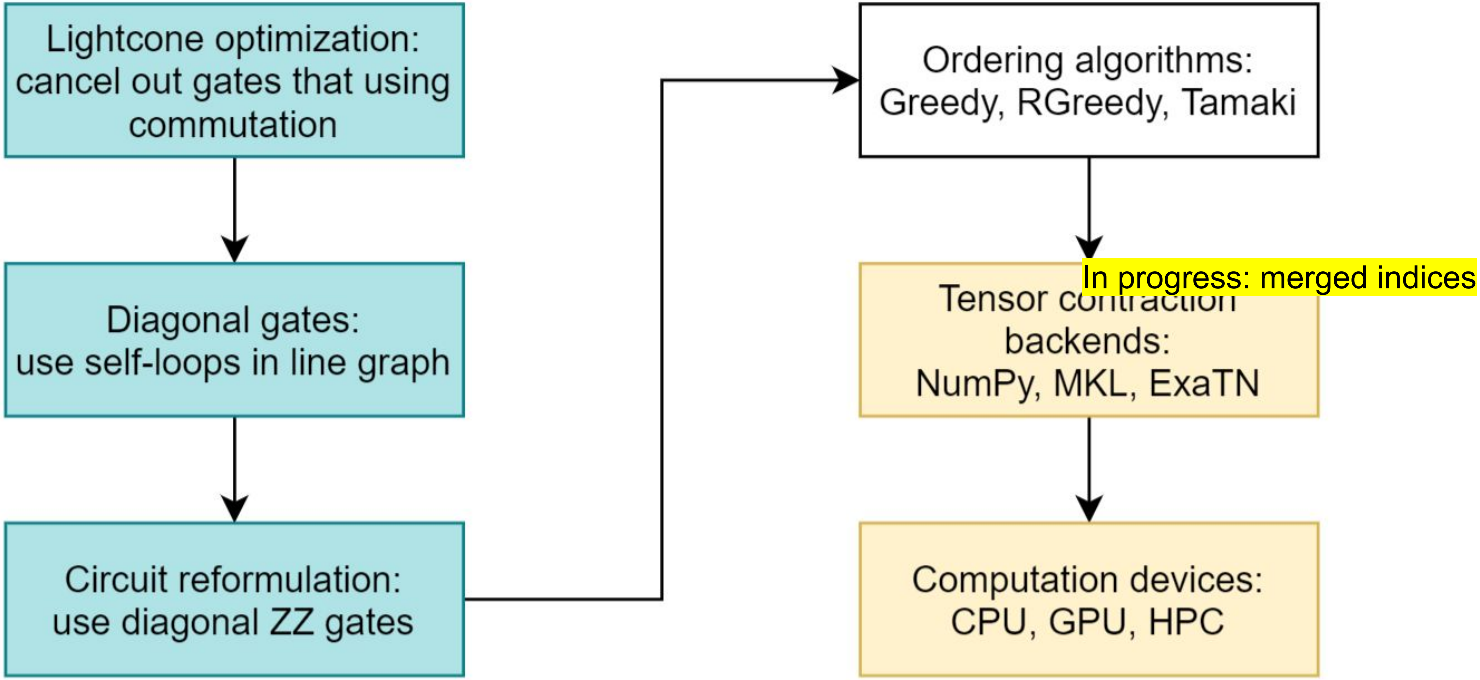
Limitations of quantum simulators

Qubits	Memory	Time per operation
10	16 KB	Microseconds on a smartwatch
20	16 MB	Milliseconds on a smartphone
30	16 GB	Seconds on a laptop
40	16 TB	Seconds on a PC cluster
50	16 PB	Minutes on modern supercomputers
60	16 EB	Hours on post-exascale supercomputers?
70	16 ZB	Days on supercomputers in distant future?

Goals of the QTensor project

1. Open source quantum simulator based on tensor network contraction schemes
2. Easy to use and integrated in popular QIS frameworks like IBM Qiskit
3. Fast simulation of certain types of circuits (QAOA and supremacy circuits)
4. Parallel distributed memory simulator designed to work on High Performance Computing (HPC) machines. In particular, it will run on exascale supercomputers Aurora and Frontier
5. Verification of quantum supremacy and advantage claims using upcoming exa-scale supercomputer Aurora for DARPA projects

QTensor Development

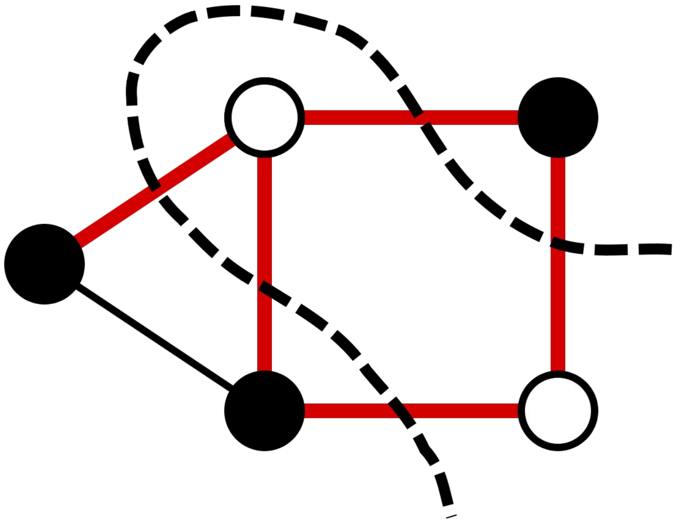


https://github.com/danlkv/QTensor

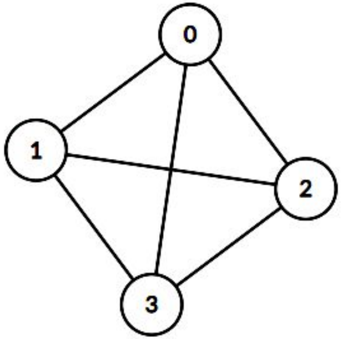
Max Cut

Assign +1 and -1 to vertices while minimizing the cost function

$$H_{\text{MaxCut}} = \frac{1}{2} \sum_{(u,v)\in E} (I - \mathrm{Z}_u \mathrm{Z}_v).$$



QAOA circuit



Fully connected graph with 4 vertices and 6 edges. The corresponding circuit to solve MaxCut problem is below

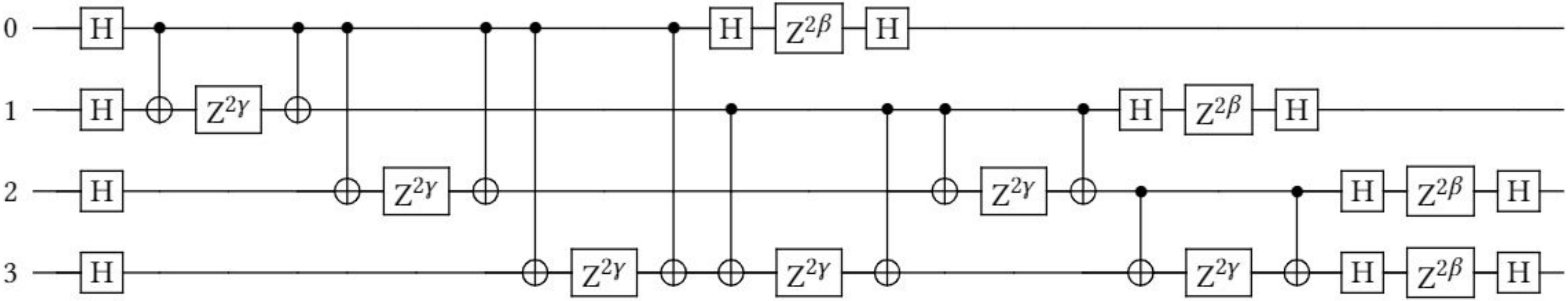


Figure 1: p=1 depth QAOA circuit for a fully connected graph with 4 nodes.

Line graph

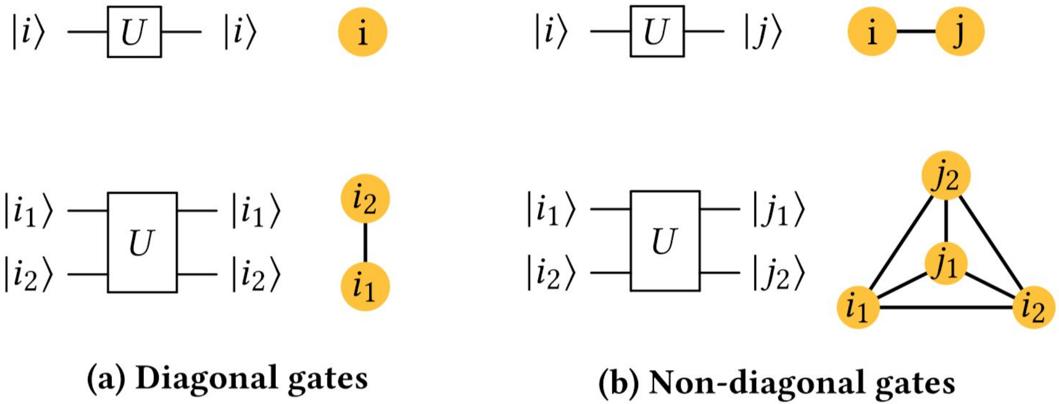
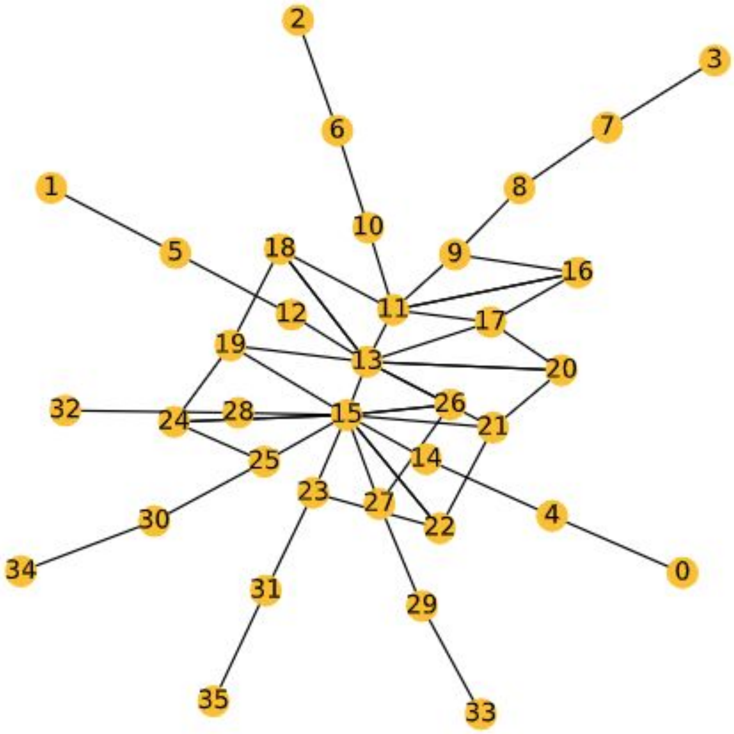


Figure 2: Correspondence of quantum gates and graphical representation.

QAOA Tensor Network



Graph representation of tensor expression of the circuit from previous slide. Every vertex corresponds to a tensor index of a quantum gate

The simulator contracts tensors in the optimal order

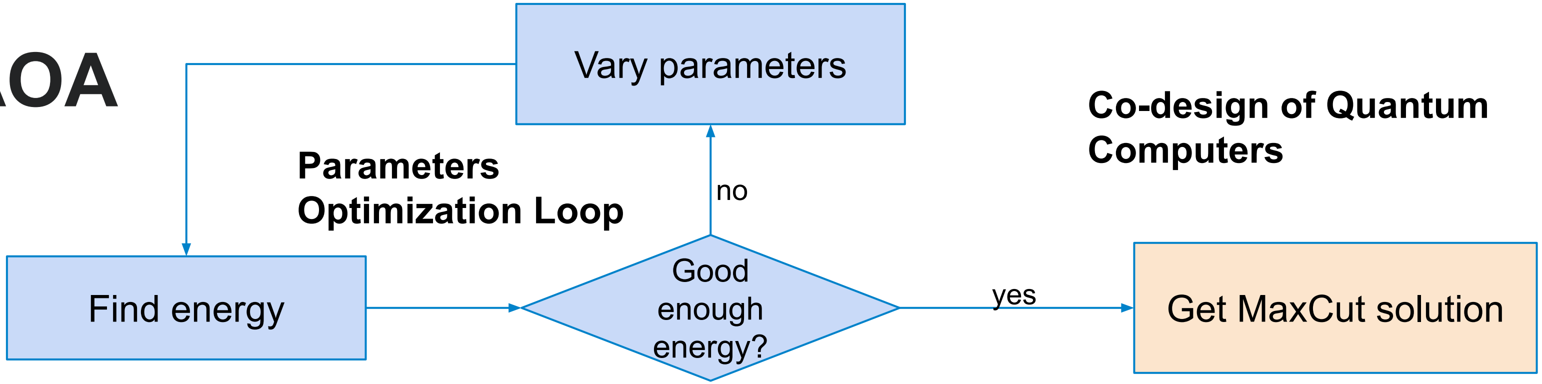
QTensor: Energy Calculations

	$d=3$	$d=4$	$d=5$
$p=1$	1.0	1.4	2.15
$p=2$	1.71	4.01	7.44
$p=3$	4	14.2	
$p=4$	9.7		

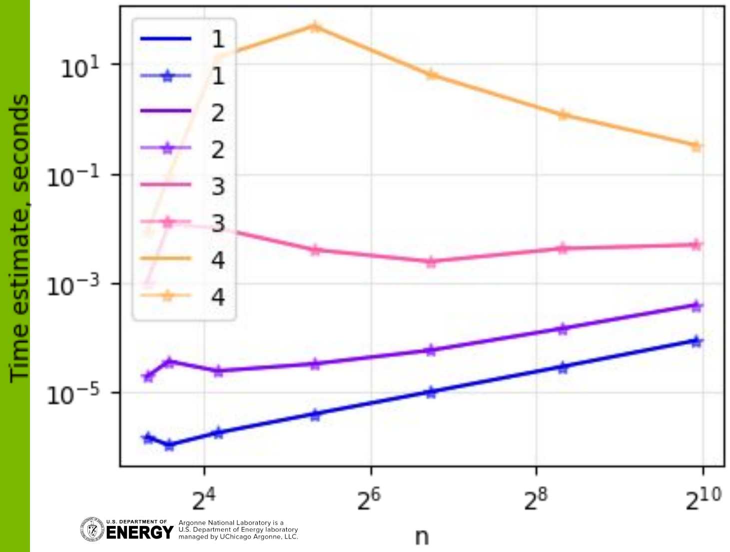
Table 1: QAOA Energy simulation time in seconds for 1000 node regular graphs. All calculations were done using QTensor simulator using NumPy backend on a single Intel Xeon Platinum 8180M CPU @ 2.50GHz with 56 physical cores.

QAOA

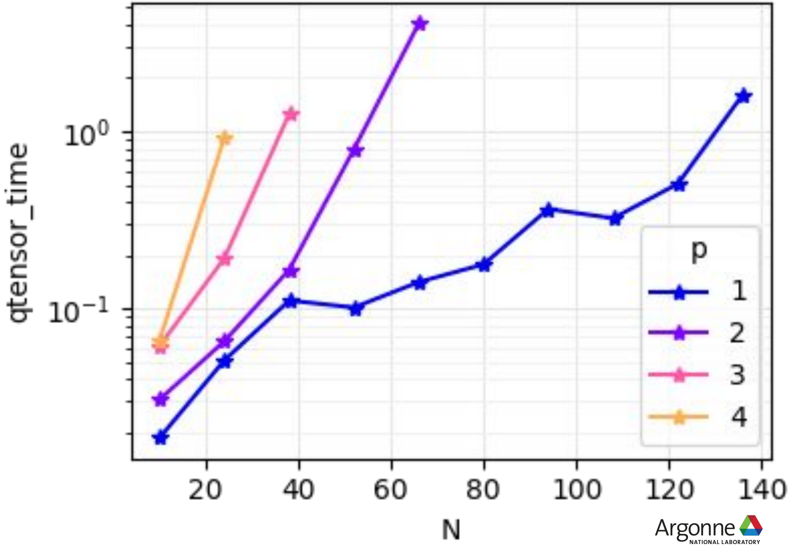
Co-design of Quantum Computers



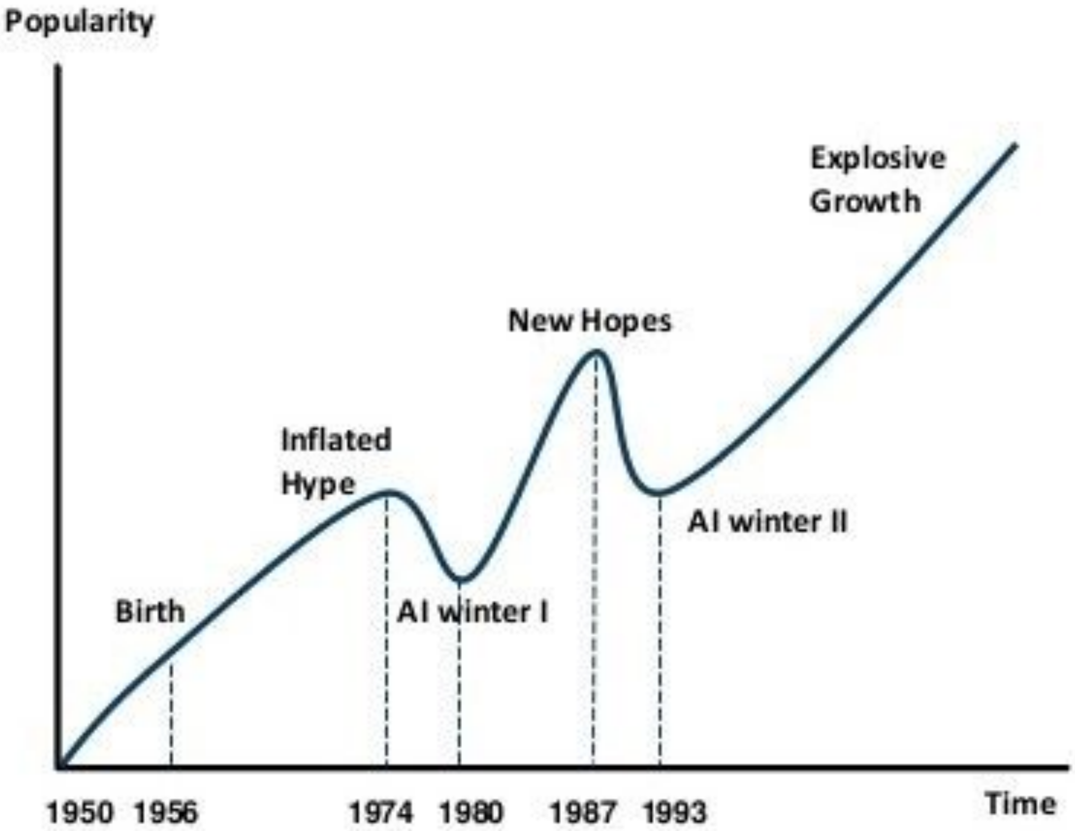
- Easy on classical



- Easy on quantum



AI HAS A LONG HISTORY OF BEING "THE NEXT BIG THING"...



Timeline of AI Development

- **1950s-1960s**: First AI boom - the age of reasoning, prototype AI developed
- **1970s**: AI winter I
- **1980s-1990s**: Second AI boom: the age of Knowledge representation (appearance of expert systems capable of reproducing human decision-making)
- **1990s**: AI winter II
- **1997**: Deep Blue beats Gary Kasparov
- **2006**: University of Toronto develops Deep Learning
- **2011**: IBM's Watson won Jeopardy
- **2016**: Go software based on Deep Learning beats world's champions

Reality check

- We have 72 noisy qubits (need millions)
- Short decoherency time to run up to 30-200 gates maximum (need millions)
- Slow gates MHz (need GHz)
- Poor connectivity (for superconducting quantum computers)
- Slow I/O

Quantum Information Science Team

Key collaborators: Prof. Ilya Safro (University of Delaware) and Prof. Alexey Galda (University of Chicago)

Postdoctoral fellows: Dmitry Fedorov and Sahil Gulania

Graduate students: Danylo Lykov, Cameron Ibrahim, Ankit Kulshrestha, Joey Xiaoyuan Liu, Henry Liu, Angela Chen

Undergraduate students: Eesh Gupta, Cody Googin, Thomas Maldonado, Huaxuan Chen

Acknowledgements

DOE ALCF: *This work used the resources of the Argonne Leadership Computing Facility,which is DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357*

DOE ECP: *This research was partially supported by the Exascale Computing Project (17-SC-20-SC), a joint project of the U.S. Department of Energy’s Office of Science and National Nuclear Security Administration, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation’s exascale computing imperative*

DOD DARPA: *This research was partially supported by the the Defense Advanced Research Projects Agency (DARPA) project*

NSF: *This material is based upon work supported by the National Science Foundation under grant EArly-concept Grants for Exploratory Research*